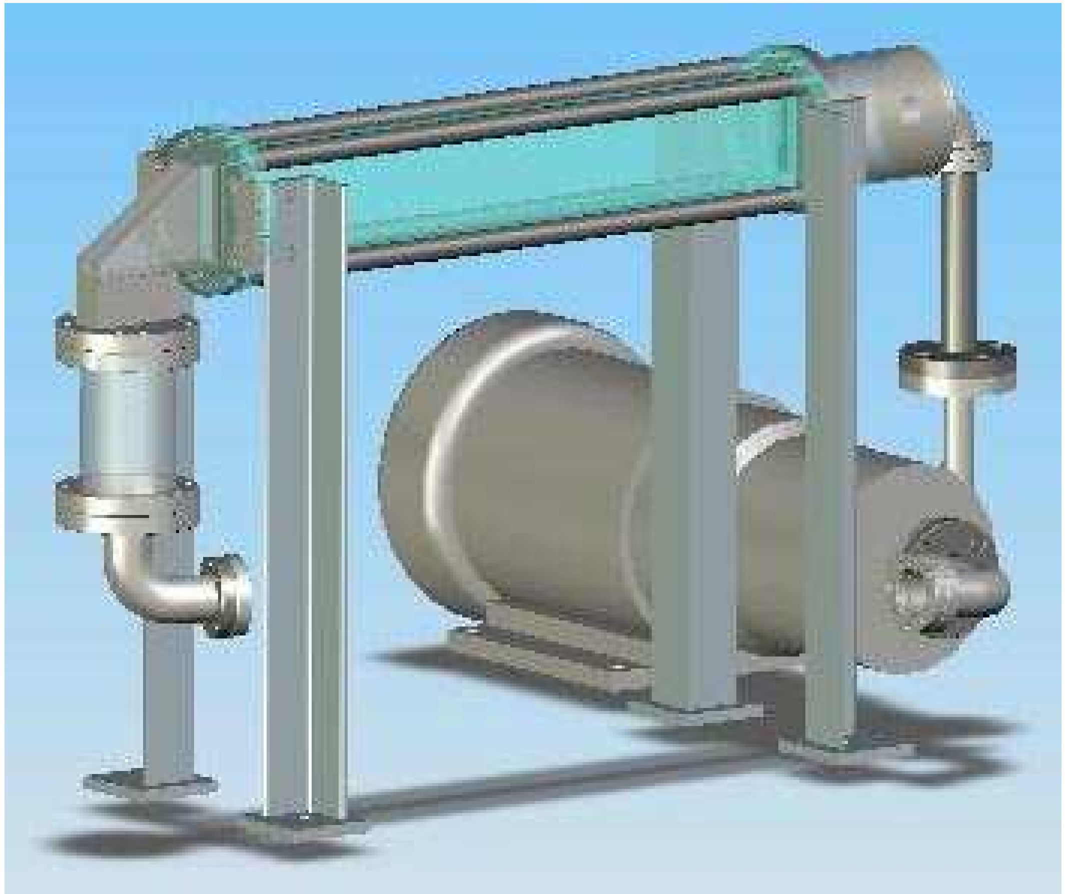
Nozzle R&D for a 20-m/s, 1-cm-diameter Mercury Jet



K.T. McDonald

Princeton U.

Neutrino Factory and Muon Collider Collaboration Meeting

February 16, 2005

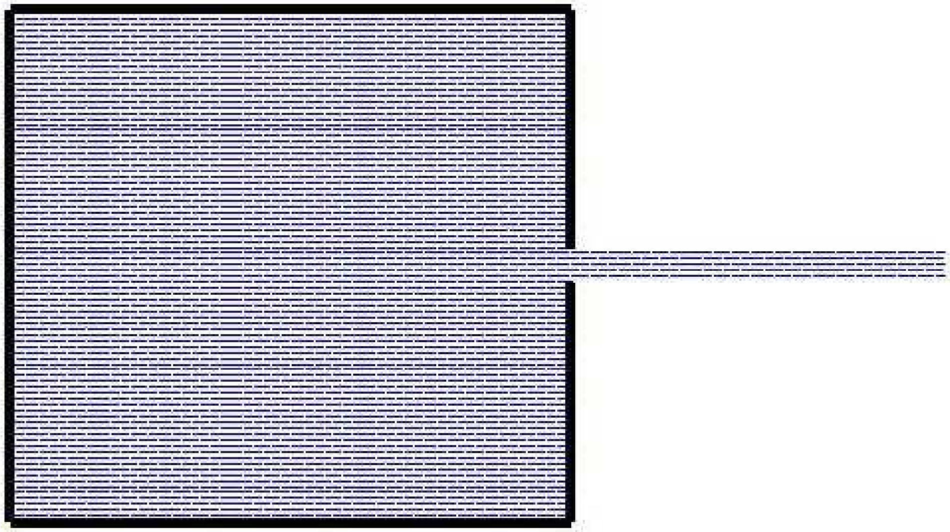
http://puhep1.princeton.edu/mumu/target/

The Best Nozzle is No Nozzle(?)

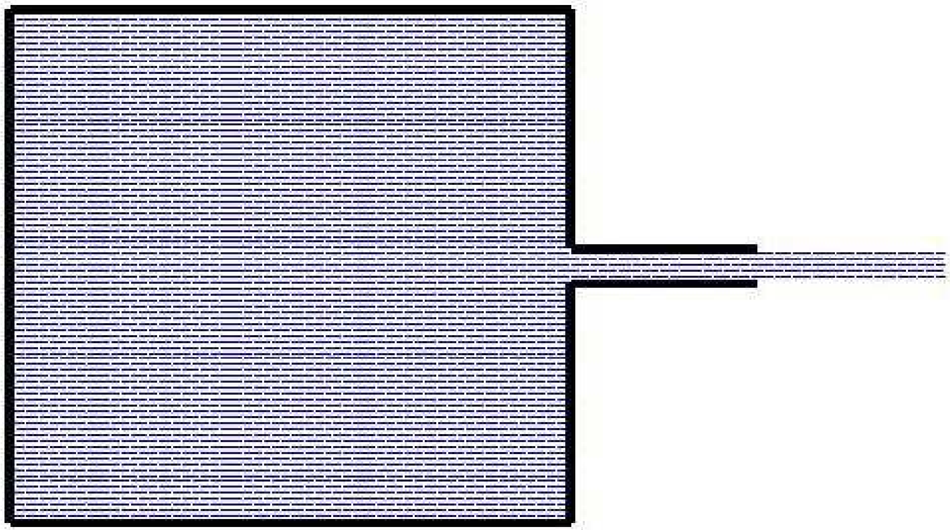
Reservoir at pressure P with small aperture:

$$v_{\text{reservoir}} \approx 0, \qquad v_{\text{jet}} \approx \sqrt{\frac{P}{\rho}}.$$

Jet emerges perpendicular to the plane of the aperture.



Reservoir + short nozzle:



No reservoir, just a straight tube. $v_{\text{jet}} = v_{\text{tube}}$:

Most nozzle R&D is concerned with making a jet break up quickly and uniformly (atomizing), rather than with preserving the jet.

Conservation of Energy *vs.* $\mathbf{F} = d\mathbf{P}/dt$ at a Contraction? (Borda, 1766)

Incompressible fluid $\Rightarrow V_1 A_1 = V_2 A_2$.

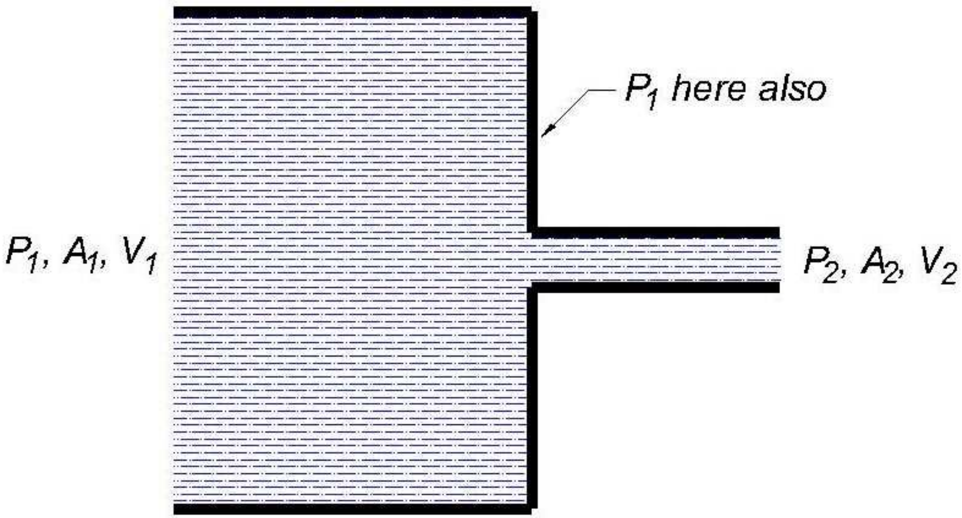
$$A_2 \ll A_1 \Rightarrow V_1 \ll V_2.$$

Conservation of Energy $\Rightarrow$ Bernoulli's Law:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2.$$

$$V_1 \ll V_2 \Rightarrow \qquad V_2^2 \approx 2\frac{P_1 - P_2}{\rho}.$$

Argument does not depend on the area.



$\mathbf{F} = d\mathbf{P}/dt$:

Mass flux $= \rho V A$.

Momentum flux $= \rho V^2 A$.

$$\begin{aligned}\text{Net momentum flux} &= \rho(V_2^2 A_2 - V_1^2 A_1) \\ &= \rho V_2 A_2 (V_2 - V_1) \approx \rho V_2^2 A_2.\end{aligned}$$

Force $\approx (P_1 - P_2) A_2$.

$$\mathbf{F} = \frac{d\mathbf{P}}{dt} \Rightarrow \qquad V_2^2 \approx \frac{P_1 - P_2}{\rho}.$$

Consistency $\Rightarrow$ dissipative loss of energy,
OR jet pulls away from the wall and contracts.

Vena Contracta

Cavitation can be induced by a sharp-edged aperture.

A jet emerging from a small aperture in a reservoir contracts in area:

$$A_{\rm jet} = \frac{\pi}{\pi+2} A_{\rm aperture} = 0.62 A_{\rm aperture}$$

$$d_{\rm jet} = 0.78\ d_{\rm aperture}$$

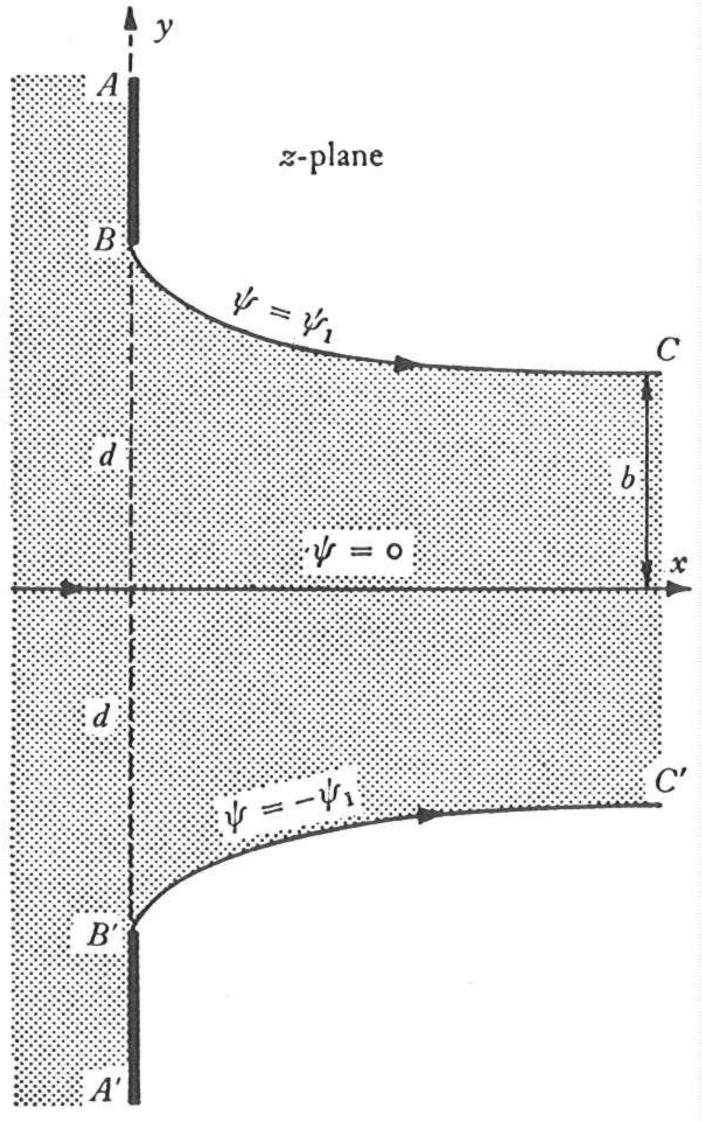
2-d potential flow (conservation of energy) $\Rightarrow$ analytic form:

$$x = \frac{2d}{\pi+2}(\tanh^{-1}\cos\theta - \cos\theta), \qquad y = d - \frac{2d}{\pi+2}(1+\sin\theta),$$

$$\theta = \text{angle of streamline}, \qquad -\frac{\pi}{2} < \theta < 0.$$

90% of contraction occurs for $x < 0.8d$.

Good agreement between theory and experiment.



Cavitation is highly likely because of the low pressure at the nozzle exit, and the high velocity in the nozzle.

- **$P_{static} = P_{stagnation} - \frac{1}{2} \rho V^2$**
  - **ρ is density**
  - **V is velocity**
  - **If $P_{static} < P_{sat}$, then mercury will cavitate**

for 20 m/s, **$\frac{1}{2} \rho V^2 = 400$ psi**

for 30 m/s, **$\frac{1}{2} \rho V^2 = 900$ psi**

- **The CFD model is not conservative in predicting cavitation due to the transient aspect of the flow which is not simulated.**
- **In the SNS Target Test Facility mitred bends, CFD results showed much less severe conditions than computed here.**

Page 54 from Handbook of Hydraulic Resistance, Idel'Chik, 3rd Edition, Begel House (1996)

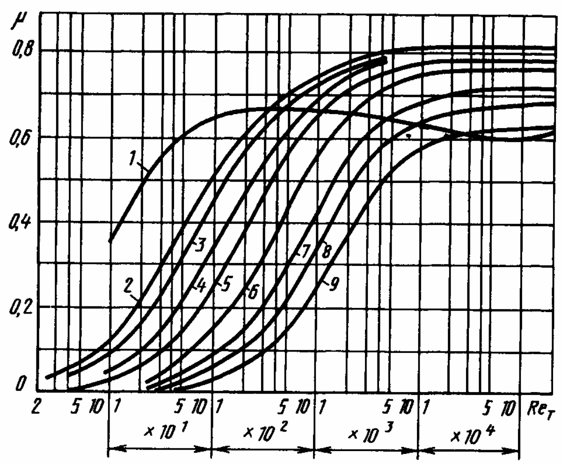


Figure 1-18 Dependence of the discharge coefficient on the Reynolds number Re for discharge from outer cylindrical nozzles:[55] (1) discharge coefficient for orifices in a thin wall; the length of the nozzle; (2) 1d; (3) 1.5d; (4) 3d; (5) 5d; (6) 10d; (7) 20d; (8) 30d; (9) 50d.

μ = V/sqrt(2/rho*(P1-P2)]

Mercury Jet Parameters

- Diameter $d = 1$ cm.
- Velocity $v = 20$ m/s.
- The volume flow rate of mercury in the jet is

$$\text{Flow Rate} = vA = 2000 \text{ cm/s} \cdot \frac{\pi}{4} d^2 = 1571 \text{ cm}^3/\text{s} = 1.57 \text{ l/s} = 0.412 \text{ gallon/s} = 94.2 \text{ l/min} = 24.7 \text{ gpm}. \qquad (1)$$

- The power in the jet (associated with its kinetic energy) is

$$\text{Power} = \frac{1}{2}\rho \cdot \text{Flow Rate} \cdot v^2 = \frac{13.6 \times 10^3}{2} \cdot 0.00157 \cdot (20)^2 = 4270 \text{ W} = 5.73 \text{ hp}. \qquad (2)$$

- To produce the 20-m/s jet into air/vacuum out of a nozzle requires a pressure

$$\text{Pressure} = \frac{1}{2}\rho v^2 = 27.2 \text{ atm} = 410 \text{ psi}, \qquad (3)$$

IF no dissipation of energy.

- The mercury jet flow is turbulent: the viscosity is $\mu_{\text{Hg}} = 1.5$ cP, so the Reynolds number is

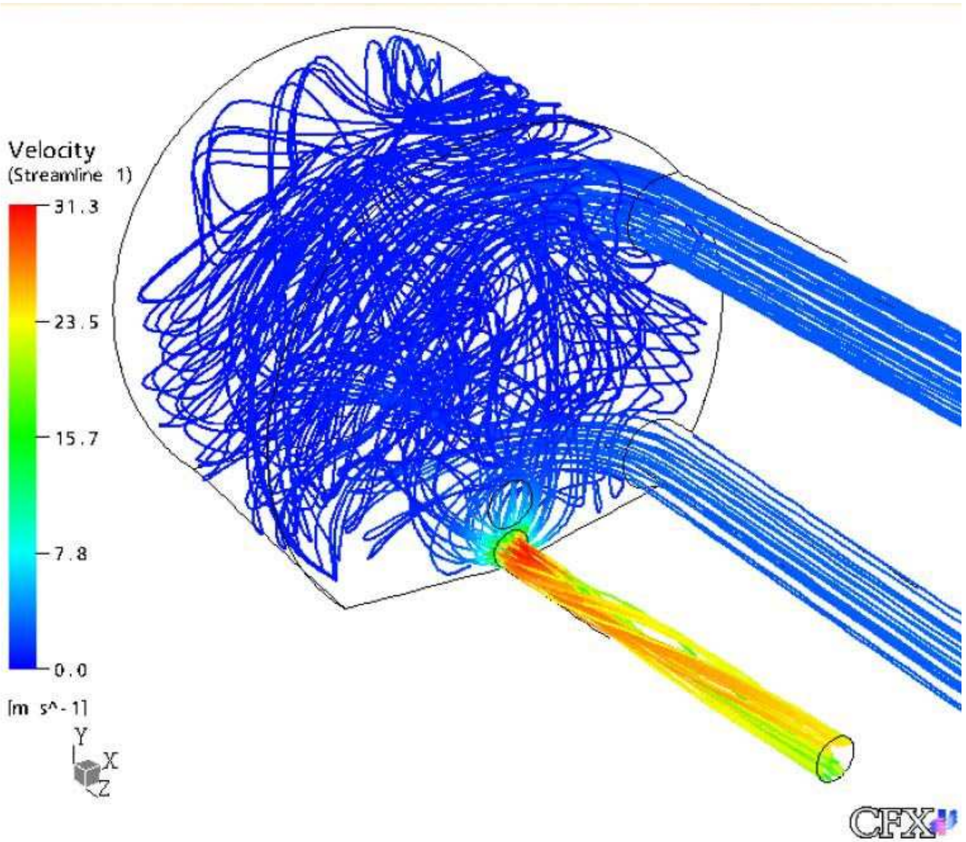
$$\mathcal{R} = \frac{\rho d v}{\mu} = 1.8 \times 10^6. \qquad (4)$$

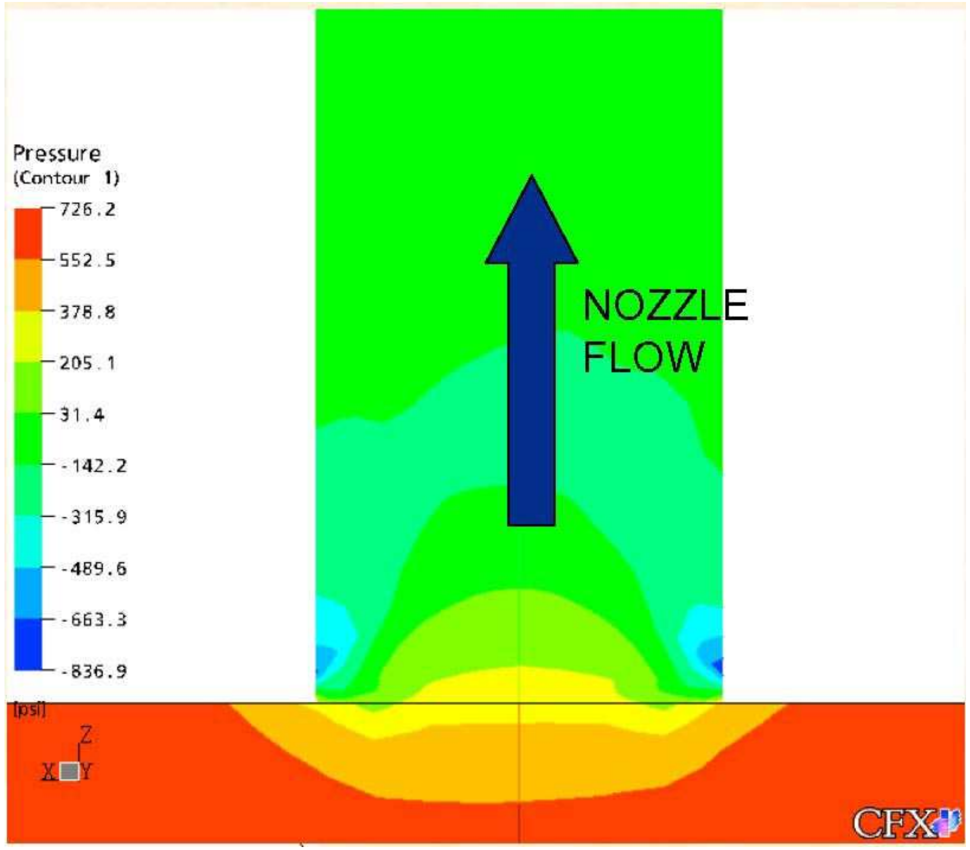
Dissipation and Cavitation Predicted by Fluid Dynamics Codes

(Mark Wendel, ORNL)

400 psi pressure drop predicted in vicinity of nozzle due to internal dissipation of energy.

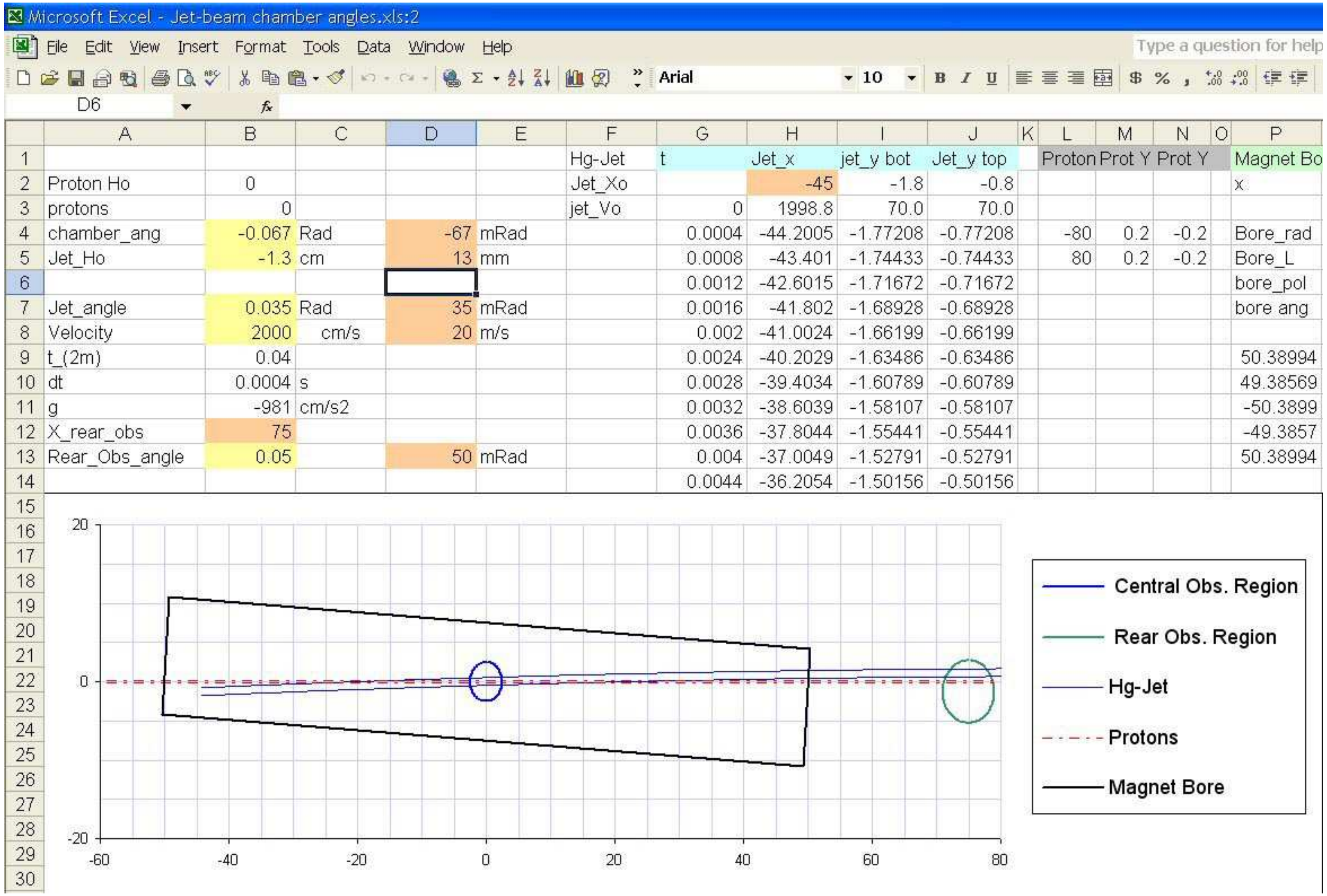
Cavitation predicted at entrance to nozzle if hard edged.





Mercury Jet + Proton Beam + 15-T Solenoid Magnet

Jacques Lettry:



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1						Hg-Jet	t	Jet_x	jet_y bot	Jet_y top		Proton	Prot Y	Prot Y		Magnet Bo
2	Proton Ho	0				Jet_Xo		-45	-1.8	-0.8						x
3	protons	0				jet_Vo	0	1998.8	70.0	70.0						
4	chamber_ang	-0.067	Rad	-67	mRad		0.0004	-44.2005	-1.77208	-0.77208		-80	0.2	-0.2		Bore_rad
5	Jet_Ho	-1.3	cm	13	mm		0.0008	-43.401	-1.74433	-0.74433		80	0.2	-0.2		Bore_L
6							0.0012	-42.6015	-1.71672	-0.71672						bore_pol
7	Jet_angle	0.035	Rad	35	mRad		0.0016	-41.802	-1.68928	-0.68928						bore ang
8	Velocity	2000	cm/s	20	m/s		0.002	-41.0024	-1.66199	-0.66199						
9	t_(2m)	0.04					0.0024	-40.2029	-1.63486	-0.63486						50.38994
10	dt	0.0004	s				0.0028	-39.4034	-1.60789	-0.60789						49.38569
11	g	-981	cm/s2				0.0032	-38.6039	-1.58107	-0.58107						-50.3899
12	X_rear_obs	75					0.0036	-37.8044	-1.55441	-0.55441						-49.3857
13	Rear_Obs_angle	0.05		50	mRad		0.004	-37.0049	-1.52791	-0.52791						50.38994
14							0.0044	-36.2054	-1.50156	-0.50156						

At the center of the magnet, the centers of the mercury jet and the proton beam should coincide.

The nozzle should be about 45 cm upstream of the center of the magnet (whose bore is 15 cm).

Mercury jet comes up from below the proton beam at about 33 mrad (35 mrad in above table).

The top of the nozzle must be at least 5 mm from the proton beam (8 mm in above table).

Corcoran Centrifugal Pump

After a search for mercury-compatible commercial pumps that could meet the above requirements, we purchased a 4000 Series, Model D-DH2(AA) centrifugal pump from R.S. Corcoran, powered by a 20-hp, 480 V motor from Baldor.

R.S. CORCORAN Co.

MANUFACTURERS : CORROSION-RESISTANT CENTRIFUGAL PUMPS • EXOTIC ALLOYED CHEMICAL PUMPS

500 NORTH VINE STREET
P.O. BOX 429
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PHONE (815)-485-2156
TOLL FREE 1-(800)-637-1067
FAX (815)-485-5840

PUMP QUOTATION

Date: APRIL 17, 2003
RSCQ #: J03041704

Attention: E. DE HAAS

c/o: PRINCETON UNIVERSITY

Pumping Application 25 GPM at 71 FT TH: (Hg) (1.56 L/S @ 420 PSI)
SOLUTION OF MERCURY, TEMP. 20-80°C, SPEC. GRAVITY 13.6

Pump **4000** **Series, Model: D-HD2 (AA)**
Description: CLOSE-COUPLED, HEAVY-DUTY DESIGN, CENTRIFUGAL
Mat'l of Const. (All wetted parts): STAINLESS STEEL

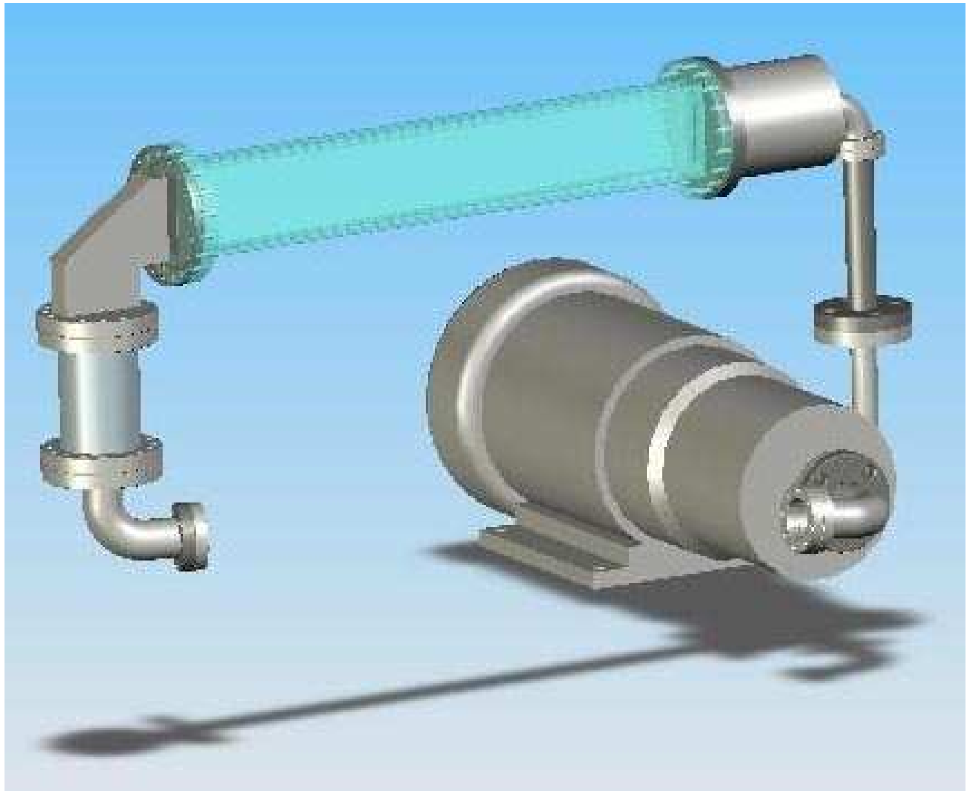
Suction: 1 1/2″ RF FLANGE (150#) Discharge: 1″ RF FLANGE (300#)
Mechanical Seal: Type 6006-8B1-40V Size 2.125
Rotating face CARBON (BALANCED) Elastomer VITON
Stationary face SILICON CARBIDE Metal parts 316 S/S
Motor: 20 HP 1765 RPM 480 Volts AC 3 Ph 60 HZ
TEFC - PREM. EFFICIENT Enclosure 1.15 SF 256TC Frame
Quantity: 1 **Unit Net Cost: $ 4952**
Shipping: 3-4 WEEKS FOB: FACTORY Approx. Shipping Wt.: 375 LBS.

Notes:
1. REFERENCE CURVE NO. 4-1501-17.
2. REFERENCE BASIC DIMENSIONAL DRAWING.
3. REFERENCE MOTOR DATA.
4. RECOMMEND SLOW START USING VFD CONTROLLER (NOT SUPPLIED BY CORCORAN).
5. **OPTION**: VFD MOTOR, 5000 RPM MAX., **NET PRICE ADDER = $572.**

Joel Kramer

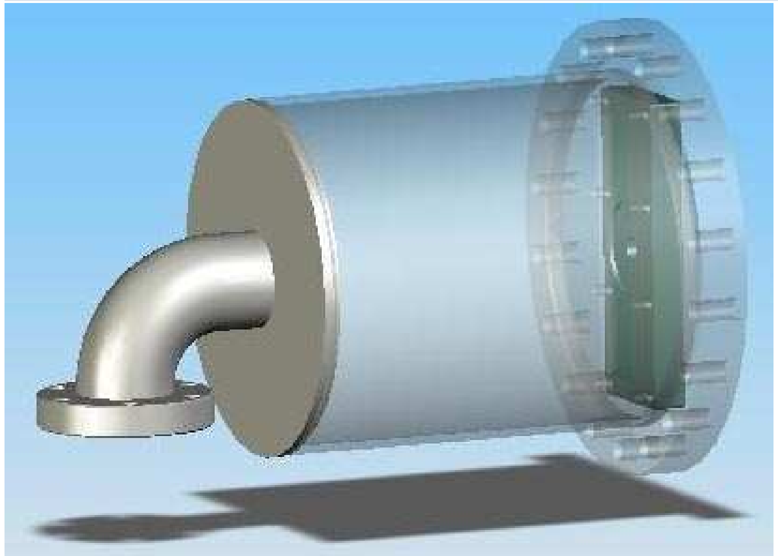
Nozzle Test Mercury Loop

Mercury loop with horizontal jet viewable for 30″ in a lexan channel.



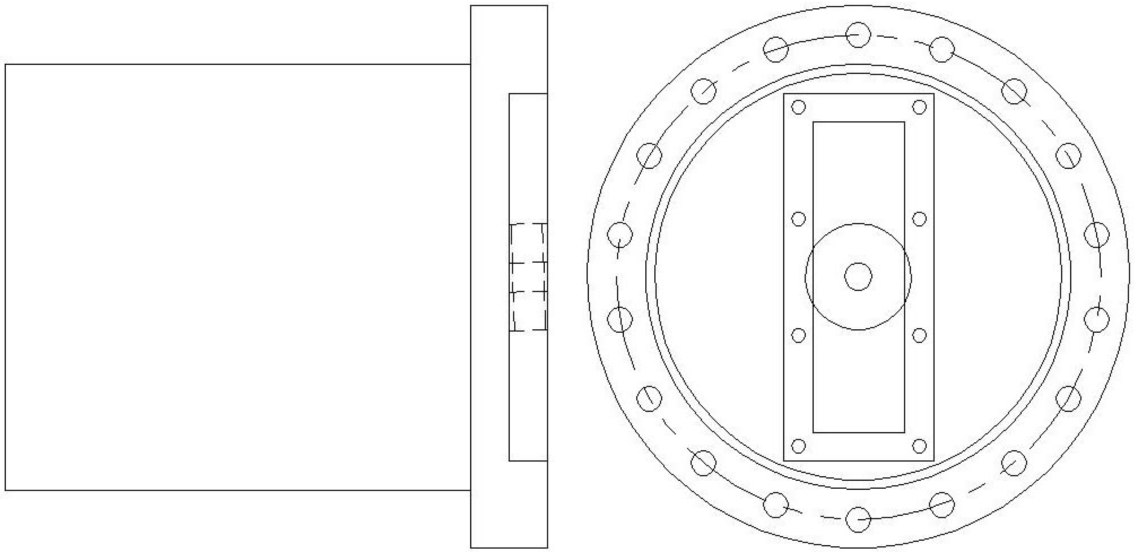
Lexan outer containment vessel sitting in a stainless-steel pan.

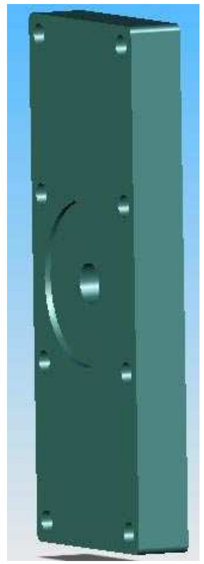
Mercury reservoir, 6″ long, 5.5″ diameter, with replacable nozzle plate.



Nozzle Plate

The aperture in the nozzle plate is tilted by 35 mrad with respect to the axis of the mercury reservoir.





Nozzle plates will be built with the aperture offset from the center, with a dummy proton beam pipe, and/or a short tube-type nozzle.